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Title: Cathodes DARHT-II Thermionic Cathode Experience

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# CATHODES

## DARHT-II Thermionic Cathode Experience

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# Acknowledgements

- Many slides copied or borrowed from work of others
  - B. Prichard
    - DARHT-II Cathode SME (2005-2010)
  - R.B. Miller
    - “A Review of Cathode Technologies for HPM Tubes”
      - Circa 2000
  - J.L. Cronin, “Modern dispenser cathodes”, IEE PROC., Vol. 128, No. 1, February 1981

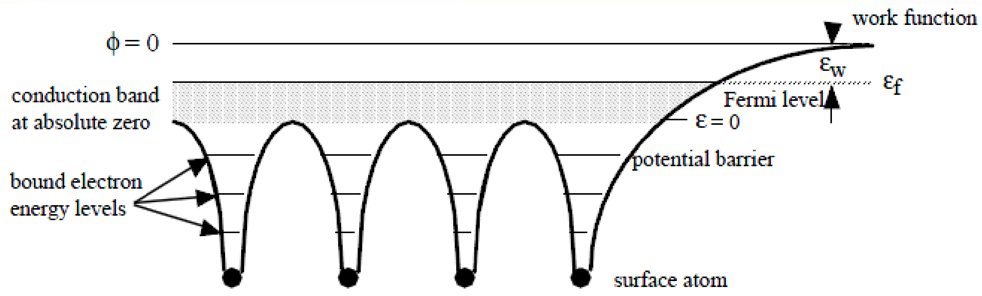
# Outline

- Types of cathodes
- Some theory
  – How do cathodes work
  – Emphasis on thermionic cathodes
- Details and some history of Axis 2 Injector and Cathodes
  – Major changes introduced in 2006-2007
- Recent experience with Axis 2 cathode

# Cathodes

- Thermionic Emission
  - Vacuum tubes, Electron Accelerators, DARHT-II
- Field Electron Emission
  - Cold Cathodes, electron microscopes, DARHT-I
- Secondary Emission
  - Gas discharge and neon lamps
- Photoelectric Emission – Photocathode
  - Phototubes, image intensifiers, polarized electron beams

# Summary of Conditions at the Surface of a Metallic Crystal Lattice




- Within the lattice, the potential energy diagram is obtained by summing contributions from adjacent nuclei.
- Inner shell electrons are bound to individual atoms.
- Outer-shell valence electrons are shared by more than one atom in the lattice.
- Q-M coupling between outer shell electrons results in the formation of energy bands.
- In metals, the lowest energy band (filled valence band) overlaps the conduction band.
  - Shared electrons can move freely under the influence of an electric field.
- At the edge of the lattice, there is no additional row of nuclei to maintain the low potential energy level.
  - The potential difference between a region far outside the surface and the bottom of the conduction band is termed the barrier height, $\varepsilon_B$.
  - The potential difference between a region far outside the surface and the top of the conduction band is termed the Fermi level, $\varepsilon_F$.
  - The difference between the barrier height and the Fermi level is the work function, $\varepsilon_W$.

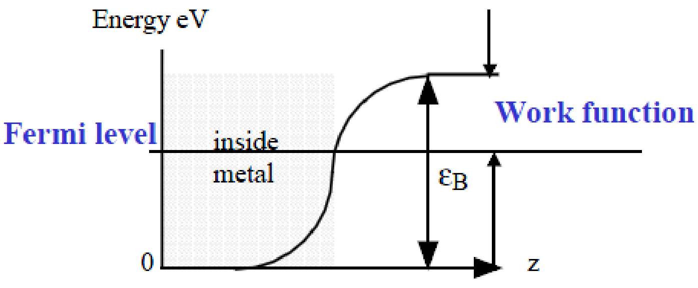
# Work Functions for Various Metals

- Assume that the zero energy level represents the bottom of the conduction band.
- Electrons in the conduction band obey Fermi-Dirac statistics
  - $f(\varepsilon) = \{1 + \exp[(\varepsilon - \varepsilon_F)/kT]\}^{-1}$

    $\varepsilon_F = 3.64\text{x}10^{-19}\, n_F^{2/3}$, $n_F = N_V / d^{\,3}$
- $N_V$ is the number of valence electrons per atom, and d is the lattice spacing.
- A crude estimate for the barrier height is

  $\varepsilon_B = 0.33\ [e^2 N_V / (\pi\varepsilon_o d)]$
- The work function is the difference between the barrier height and the Fermi level:

  $\varepsilon_W = \varepsilon_B - \varepsilon_F = 8.3 - 6.9 = 1.4$ eV, for Cs
  ($N_V = 1$, and d = 2.3 Angstroms)




| Metal | $\varepsilon_w$ (eV)* | Melting Point (oC) |
|---|---|---|
| Aluminum | 3.7 | 660 |
| Barium | 2.3 | 725 |
| Carbon | 4.4 | ~3550 |
| Cesium | 1.9 | 28 |
| Copper | 4.5 | 1083 |
| Gold | 4.6 | 1064 |
| Iridium | 5.2 | 2410 |
| Iron | 4.4 | 1535 |
| Molybdenum | 4.3 | 2620 |
| Osmium | 5.4 | 3045 |
| Rhenium | 5.1 | 3180 |
| Thorium | 3.4 | 1750 |
| Tungsten | 4.5 | 3410 |

**Pure metals with low work functions have low melting points.**

# Emission Mechanisms

- Supply additional energy to electrons in the conduction band such that $\varepsilon > \varepsilon_W$.
  - thermionic emission (apply heat - 1000 °C)
  - photoemission (apply photons with $h\nu > \varepsilon_W$; 4000 Ang. = 3.1 eV)
  - secondary emission (electron bombardment; > 100 eV)

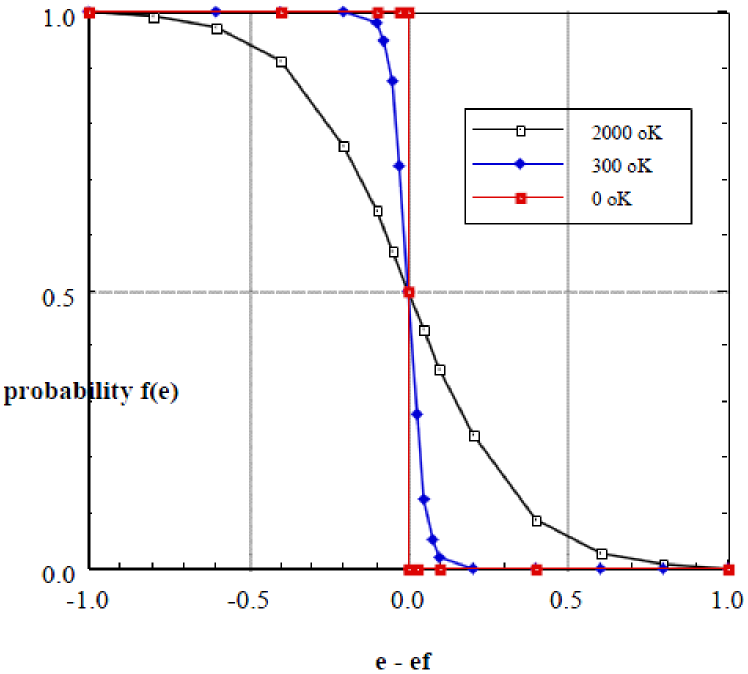
- Modify the potential barrier.
  - field emission (apply a very strong electric field; $10^7$ V/cm)
  - explosive emission (form a plasma on the surface; $\varepsilon_W = 0$)

At present, the important emission mechanisms for high-power tubes include

thermionic emission
explosive electron emission

# Thermionic Emission

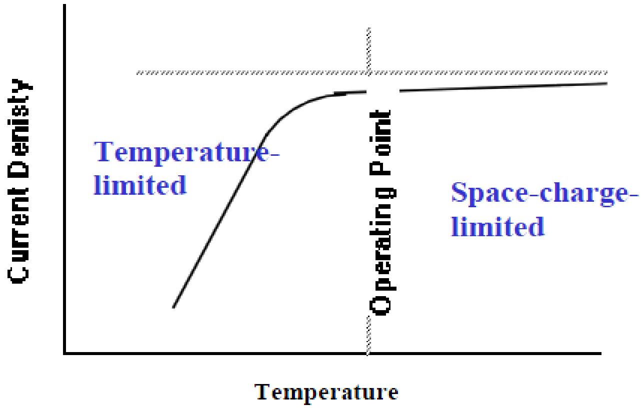
- The kinetic energy of electrons in the conduction band depends on the temperature.
  - $f(\varepsilon) = \{1 + \exp[(\varepsilon - \varepsilon_F)/kT]\}^{-1}$
- The critical z-directed momentum for escape from the surface is
  - $[p_{zc}^2/(2m)] > \varepsilon_B = \varepsilon_F + \varepsilon_W$
- The emission current density is found by integrating the +z directed current of electrons in the conduction band over all momentum states.
- The result is the Richardson-Dushman equation:
  - $j\ (\text{amps/m}^2) = 1.2 \times 10^{-6}\, T^2 \exp(-\varepsilon_W/kT)$

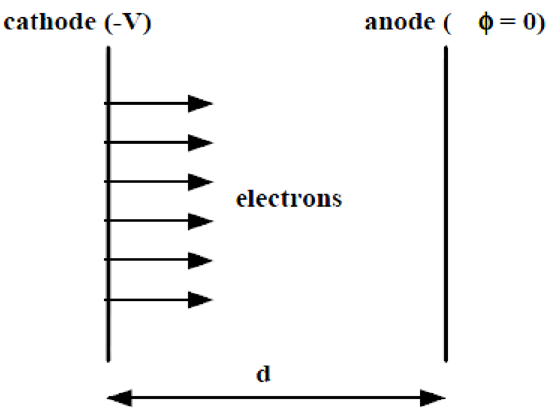



**The thermionic emission current density is a function of the temperature and the work function.**

# Space-Charge Limited Flow

- The current density from a thermionic cathode is temperature-limited at low temperatures, and space-charge-limited at high temperatures.
- Thermionic cathodes are usually operated just into the space-charge-limited region.
  - This eliminates the need for precise temperature and work function uniformity over the surface, and eases voltage and current stability requirements for the cathode heater.
- The critical assumptions for estimating the space-charge limit are the following:
  - the electric field *vanishes* at the cathode surface
  - the emitted electrons have *zero* initial velocity
- The one-d planar diode result is given by the Child-Langmuir law:
  - $j = (4/9)\,\varepsilon_o (2e/m)^{1/2} (V^{3/2}/d^2)$
  - $= 2.33 \times 10^{-6} (V^{3/2}/d^2)$ (amps/m$^2$)




- **Current can be increased by:**
  - **Higher voltage**
  - **Larger area**
  - **Reduced anode/cathode distance**

# Child-Langmuir Law (Perveance)

- Child (1911) showed that the space-charge limited current in a plane parallel vacuum diode varies directly as the 3/2 power of the anode voltage, $V_a$, and inversely as the square of the distance, d, from the anode to the cathode.

$$J = \frac{I_a}{S} = \frac{4\epsilon_0}{9}\sqrt{2e/m_e}\,\frac{V_a^{3/2}}{d^2}.$$

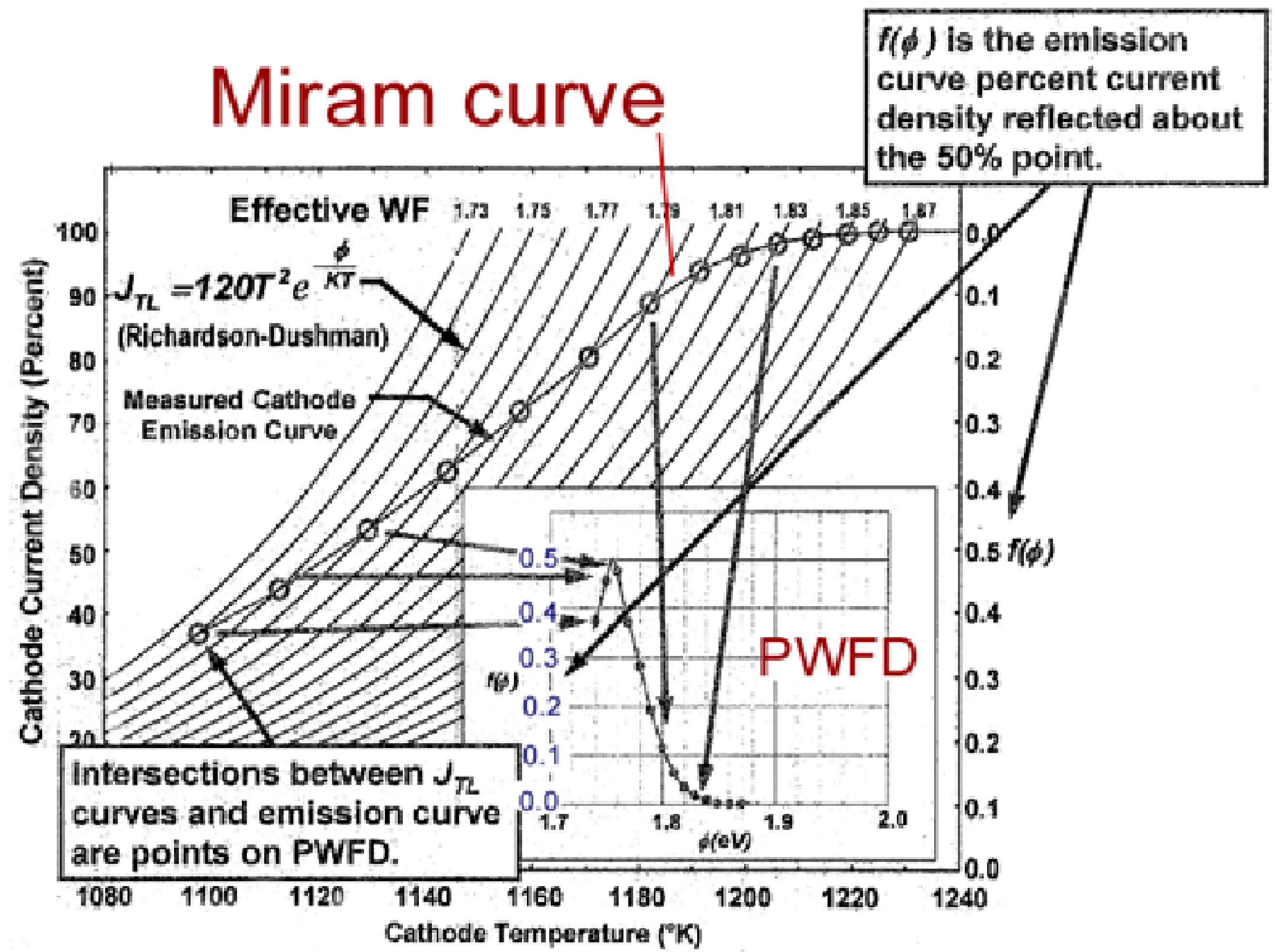
  – Where J is the current density, $I_a$ is the anode current, S is the surface area

- Langmuir (1913) extended the application to cylindrical anodes and cathodes

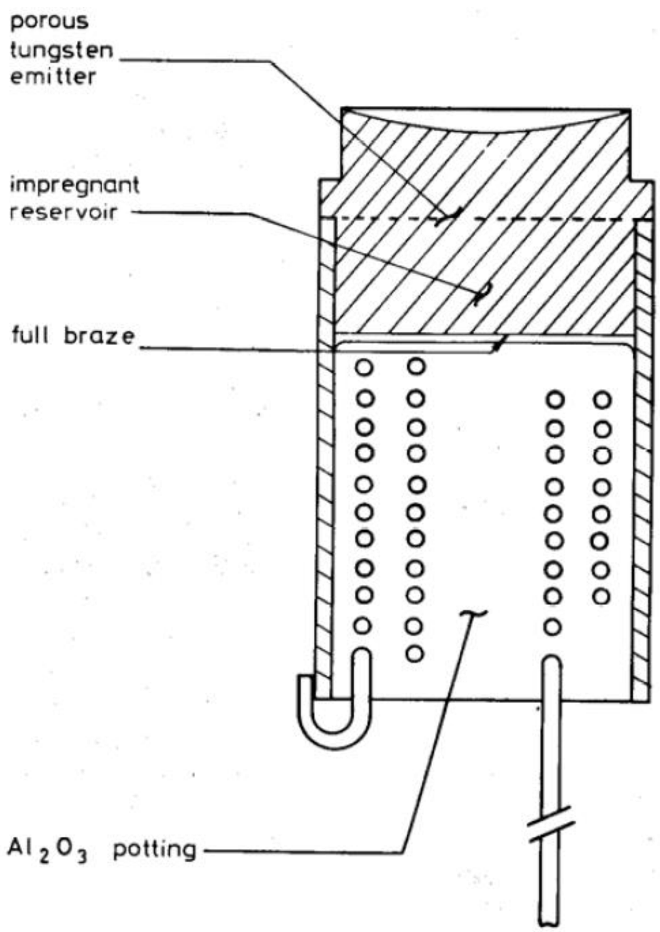
$$I = kV^{3/2}$$

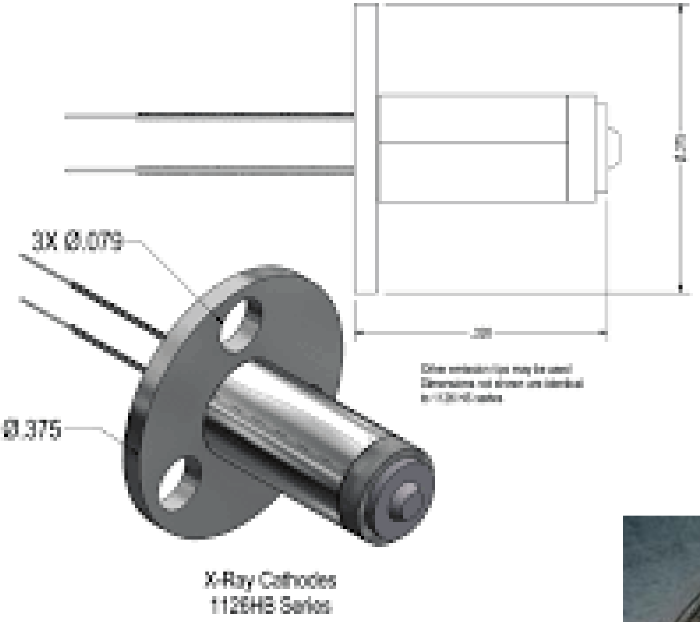
  – Where k is known as the perveance and is a function of the geometry
    - A typical perveance is ~$10^{-6}$ when V is measured in Volts and I in amperes
    - For DARHT-II, k is ~0.54 uPervs

# The Practical Work Function Distribution (PWFD) is determined from the Miram Curve



# Cathode examples

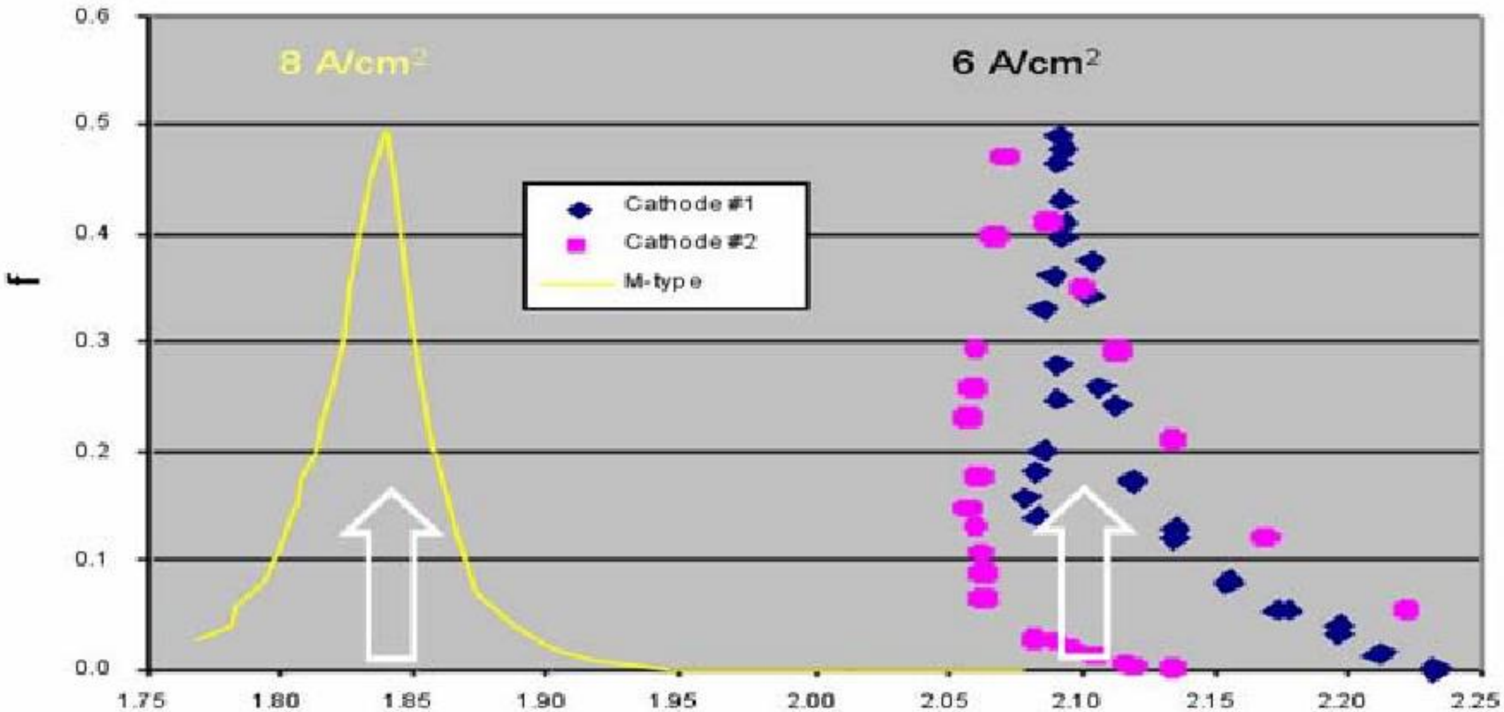



# The DARHT-II cathode is the largest dispenser cathode in the world

- Requirements
  - 2.0 kA for 2 microseconds
  - 6.5” diameter planer cathode
    - An 8” diameter cathode was also studied
  - 10 A/cm$^2$ current density
- Initial performance (pre-2006) did not meet requirements
  - Maximum observed current of 1.25 kA
  - Reduced current output over time suggesting “poisoning”
  - 612M cathode
  - A June 2006 Jason Review concluded the present injector cannot reach the DARHT-II design requirements and acknowledged a well structured development program was in place
- Extensive modifications were made
  - 311X-M cathode
  - A-K gap reduced
  - Improved vacuum pumping in cathode shroud
- Design requirements were met in late 2007

# The measured effective cathode work function was higher than expected (pre 2006)




Expected performance ~1.85 eV

Measured performance ~2.1 eV

# Cathode Status (pre 2006)

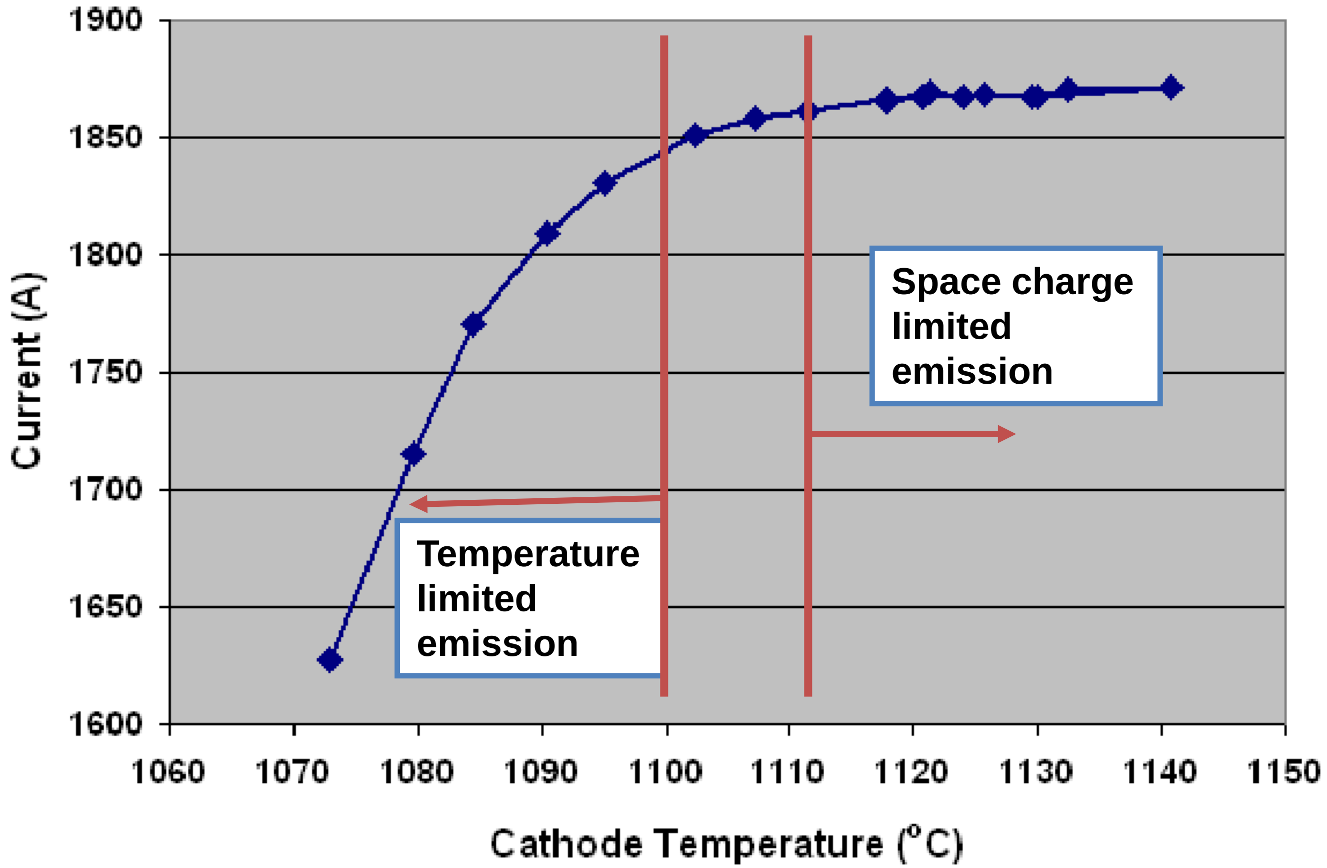
- The effective cathode work function is higher than properly performing M type cathodes
- Cathode activation procedures were reevaluated and carefully monitored to ensure proper surface preparation
- Microscopic autopsy of used cathodes showed no obvious fabrication flaws
- Cathode temperature profiles could be improved but are good enough

# Increasing the current from ~1 kA to ~2 kA can be achieved in two straightforward ways

1. Raising the voltage from ~2 MV to ~3.2 MV
   – Limiting voltage to 2.5 MV increases column reliability
2. Reducing the Anode-Cathode (A-K) gap (d) to ~10" from the current gap of ~13"
   – The cathode shroud was modified by changing the support struts and extending the shroud extension cover
   – The current density is inversely proportional to $d^2$

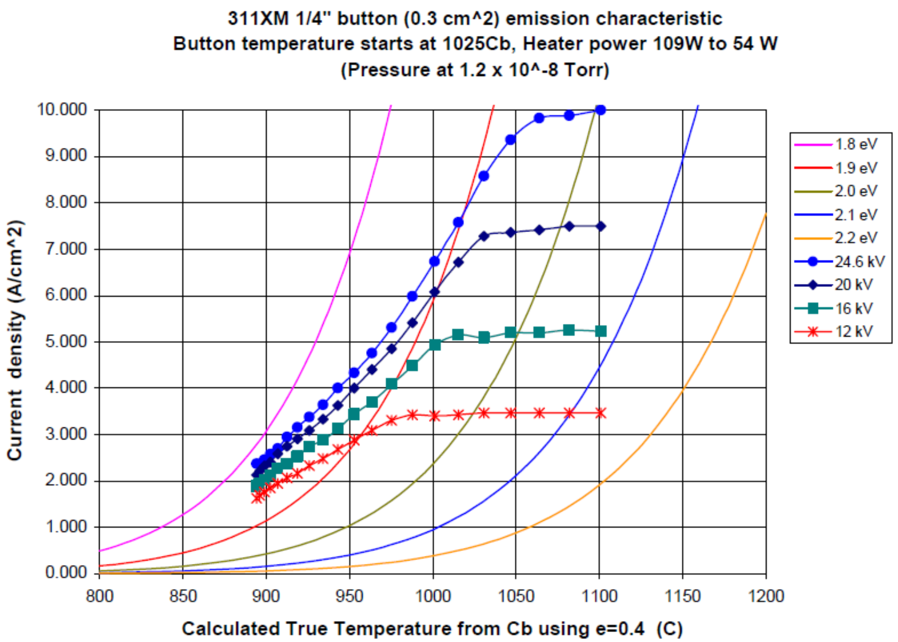
NOTE: Increasing the field gradient requires a matching current density increase from the cathode. Increasing the cathode temperature alone is unattractive due to lifetime limitations. A lower effective cathode work function is needed.

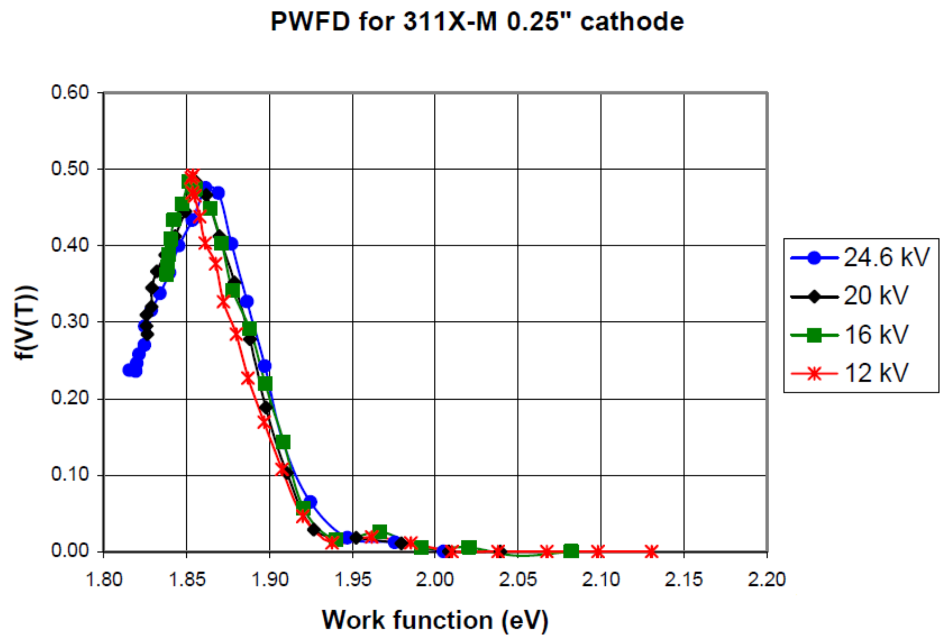
# Cathode Current vs Temperature



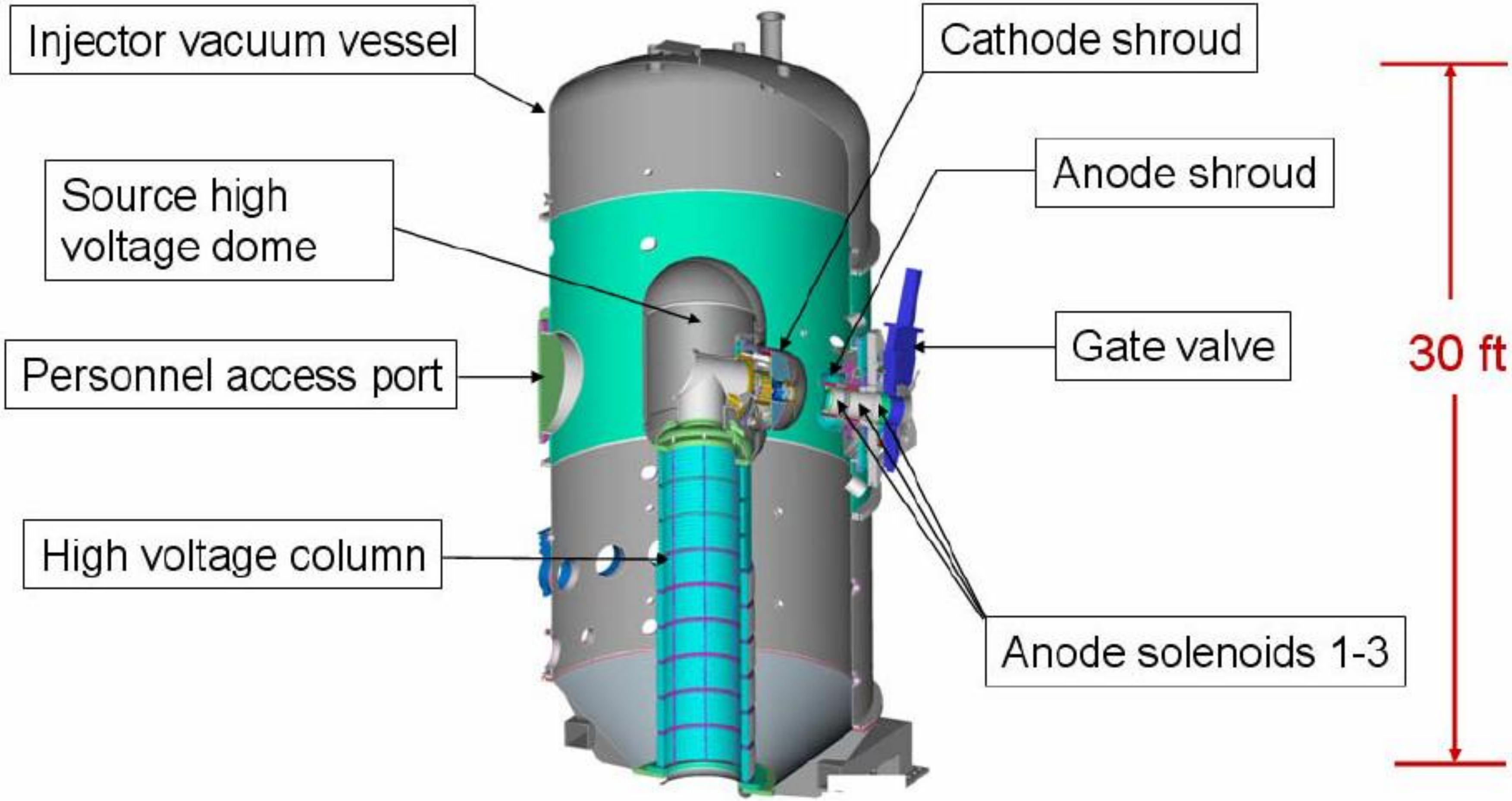

**Data taken at 2.3 MV (34.5 kV charge voltage)**

# Miram Curves for Small 311X-M Cathode on LBNL Test Stand demonstrated required performance

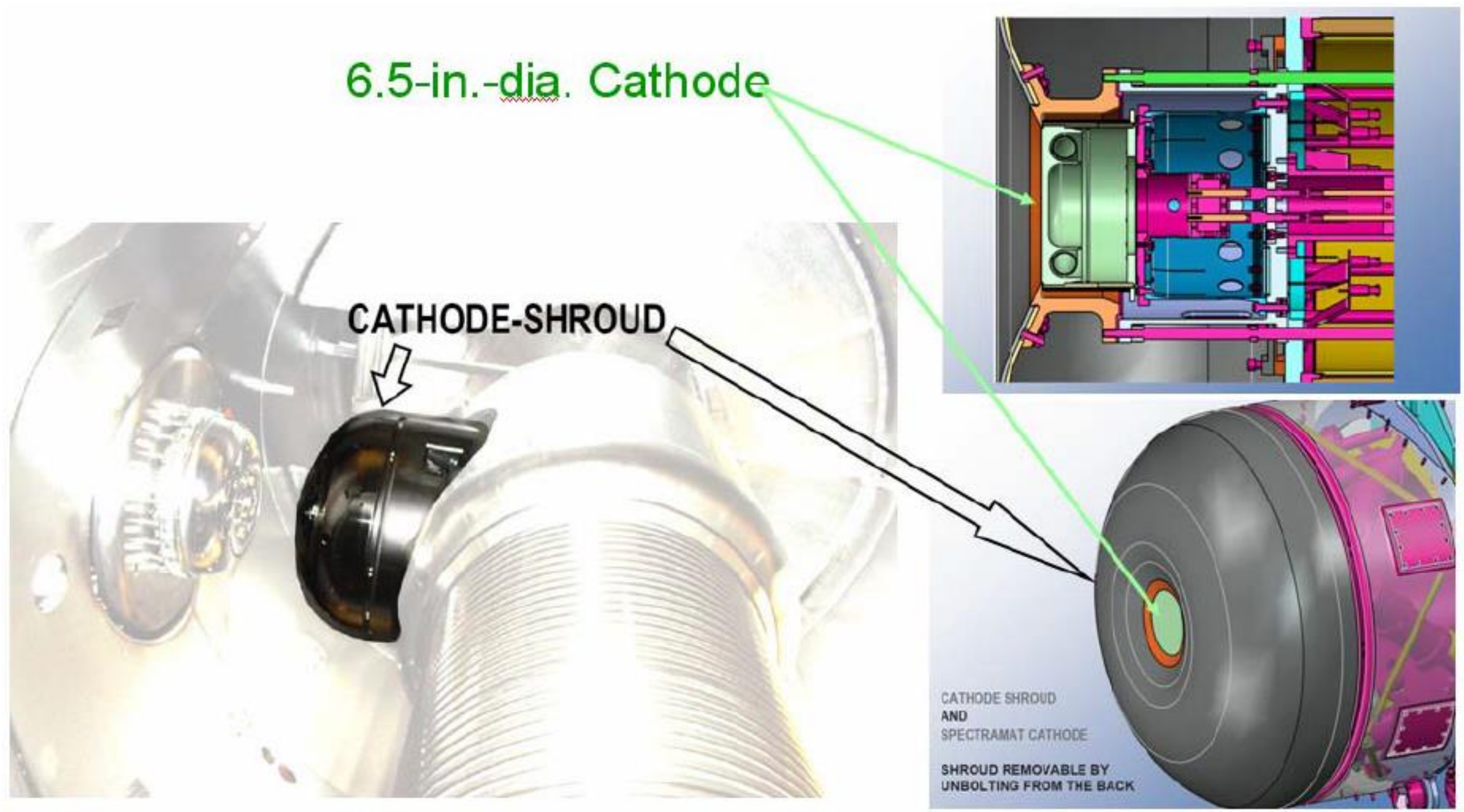


# DARHT-II Injector Vacuum Vessel



# 6.5 inch Cathode located in 3 foot diameter shroud



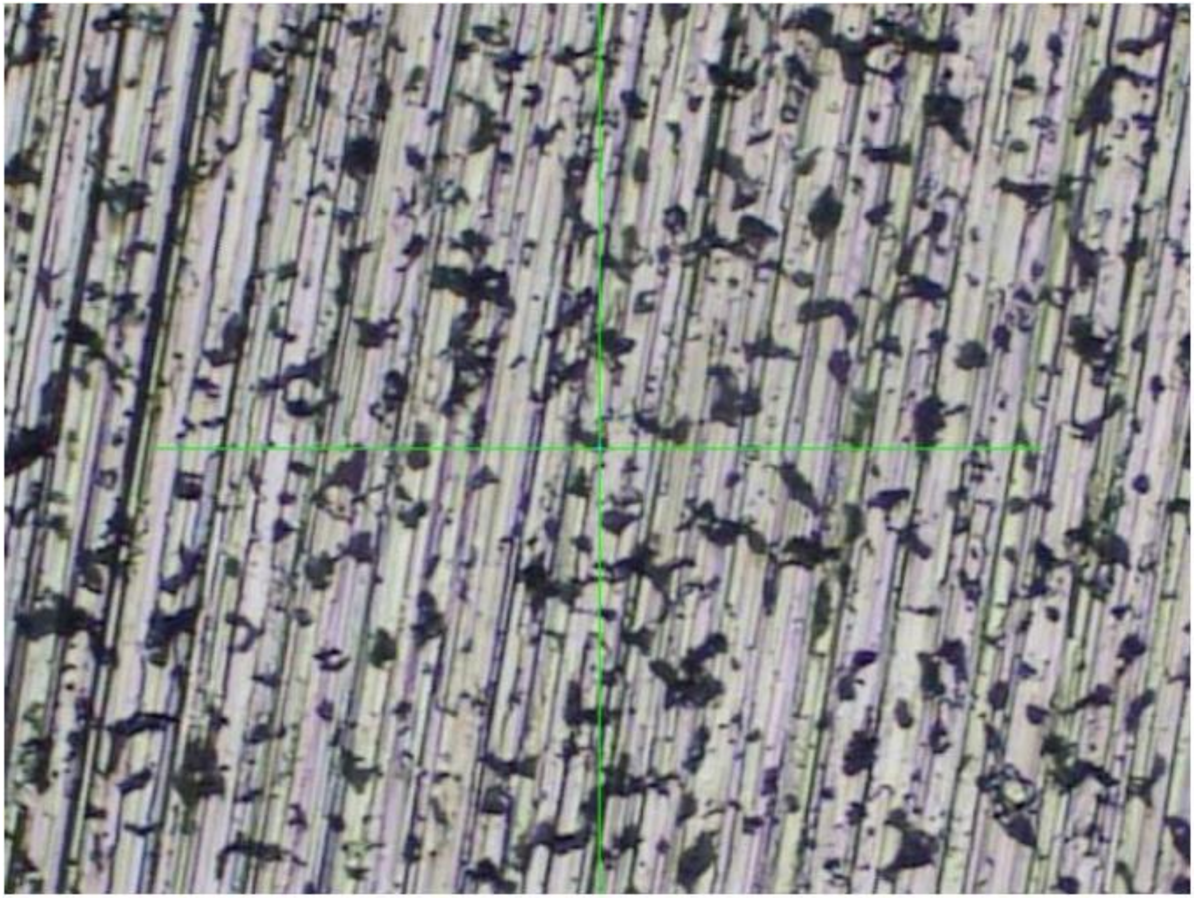
# 311X-M Cathode

- Porous sintered Tungsten substrate
- Impregnated with Barium Oxide (BaO), Calcium Oxide (CaO) and Aluminate ($Al_2O_3$) in 3:1:1 molar ratio
- Additional scandate ($Sc_2O_3$) impregnate to improve emission at low temperatures (X designation, lower sensitivity to poisoning at elevated pressures)
- M coating - Osmium-Ruthenium (OsRu) to reduce emissivity and work function(0.5 um)

# Cathode Processing and Activation

- Minimize exposure to air during installation
- Maintain a pressure “at the cathode” of $10^{-7}$ torr or better
- Raise the temperature to about 400°C and allow to “soak” for a minimum of 12 hours
  - Eliminate water vapor
  - Breaks down hydrates formed with the Ba-Ca-Aluminates
- Raise the temperature to about 875°C and hold for at least 12 hours
  - $W_2O_5$ (tungstate) breaks down and combines with hydrogen to form clean tungsten
- Activation is achieved by converting BaO to free barium in the tungsten matrix
  - Hold temperature at 50-100°C above operating temperature without exceeding 1200°C

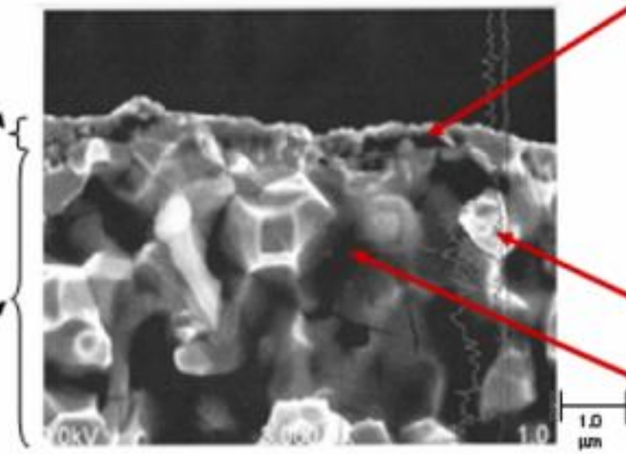
# Cathode Surface after final machining prior to M coating (960x)



# Microscopic examination of used cathodes reveal no basic fabrication flaws

Os-Ru coating

Porous Tungsten with Barium impregnate



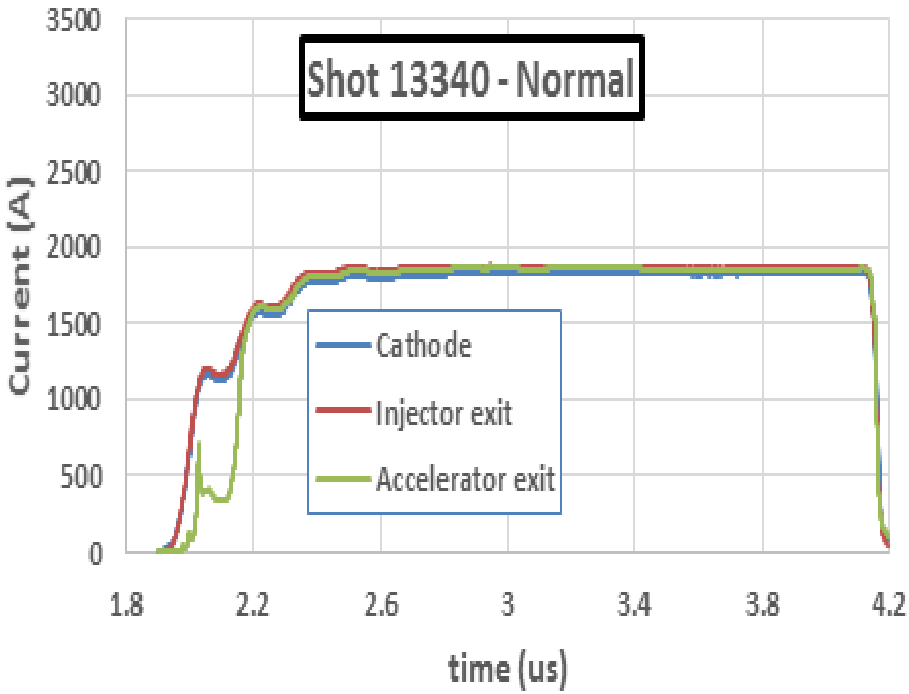

Typical acceptable microstructure observed

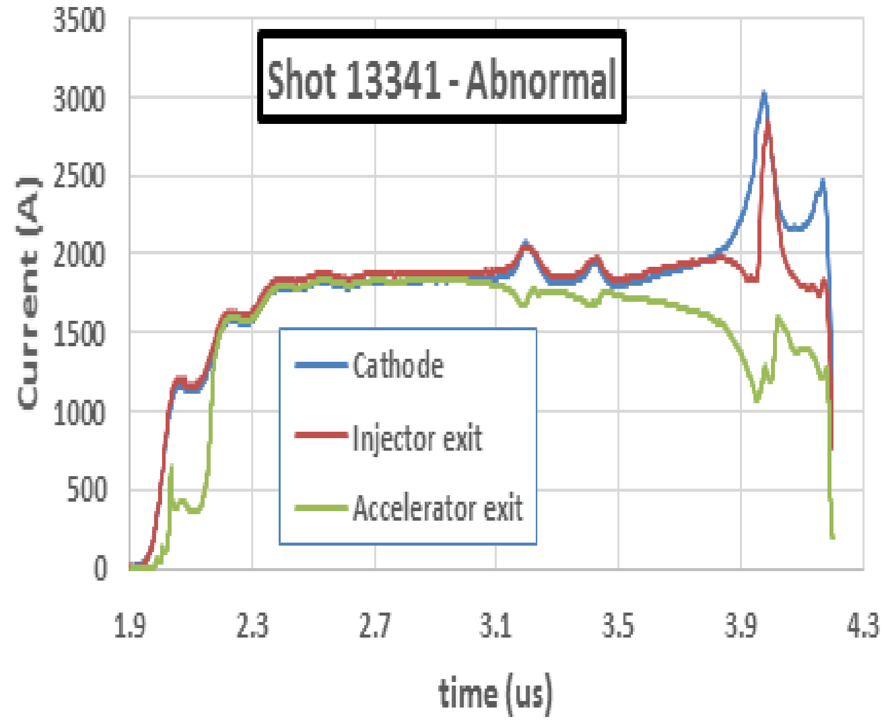
- Potential fabrication issues affecting performance
  - Proper coating
    - Smoothness
    - Thickness
    - Flaking
    - Tungsten protrusion
  - Tungsten grain size
  - Adequate pores for Barium Migration
  - Effects of surface machining

# 2007-2013 Experience

- **Seven subsequent cathodes lasted an average of about six months before requiring replacement (2009-2013)**
  - New filament design to eliminate turn-to-turn shorts and shorts to ground (one cathode)
  - Extensive peeling of Os-Ru coating often resulting in explosive emission (six cathodes)
- **Modifications to cathode fabrication and activation processes were implemented in early 2013**
  - Modifications appear to have eliminated the problem of Os-Ru “peeling” and greatly improved cathode lifetime and performance
  - Peeling of Os-Ru coating can result in explosive emission rather than thermionic emission
  - Peeling of Os-Ru coating is somewhat well documented in the literature
  - Correlated with loss-of-power events

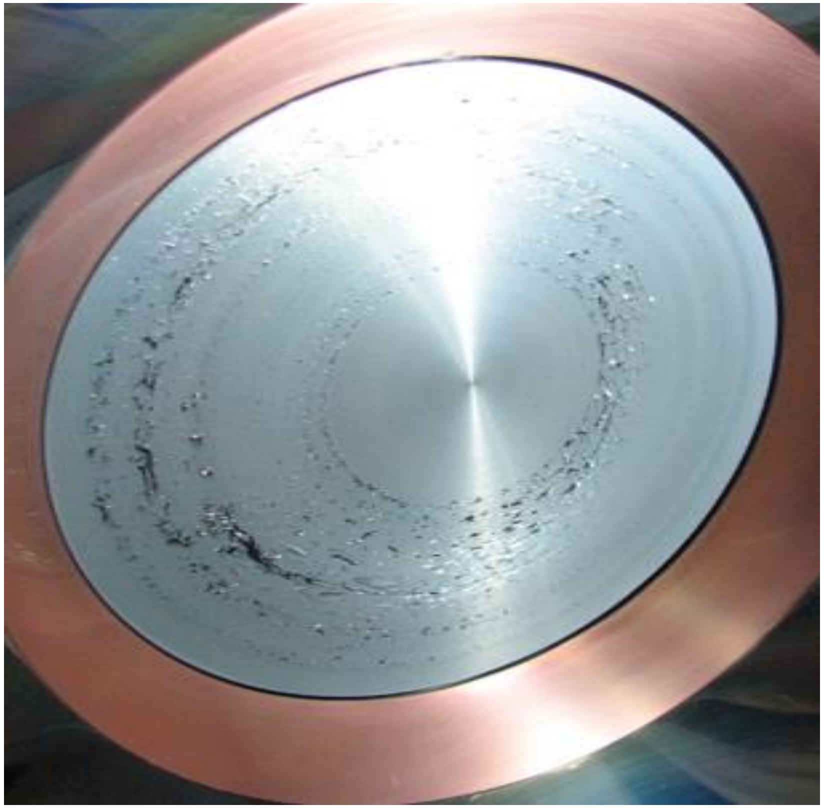
# Abnormal cathode emission first observed on 10-26-10

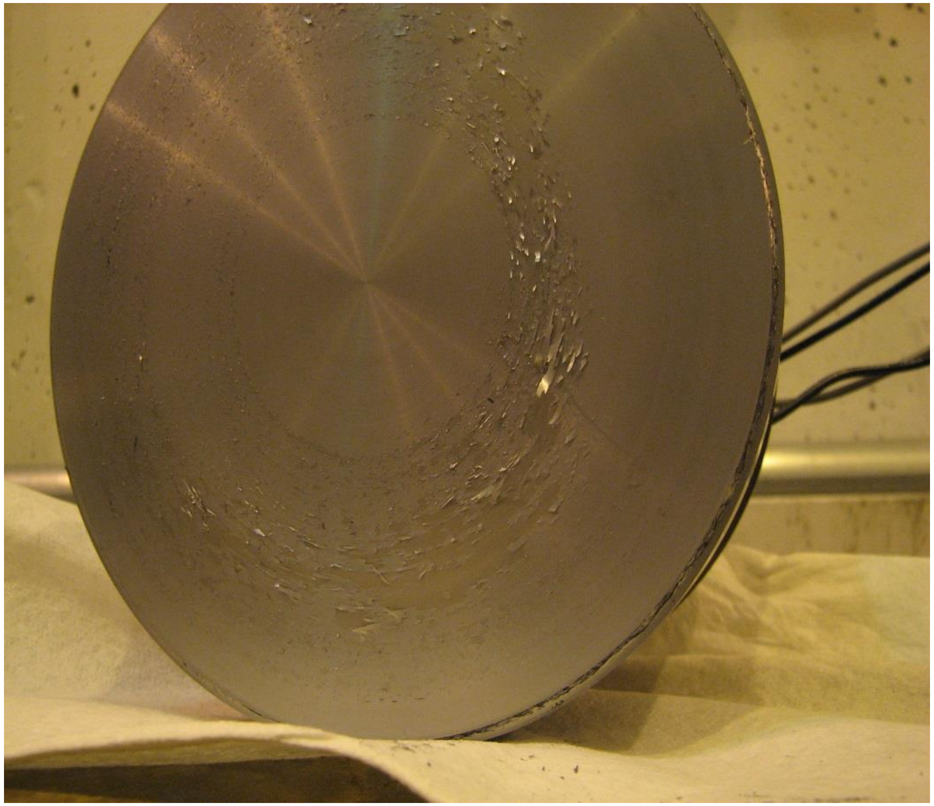


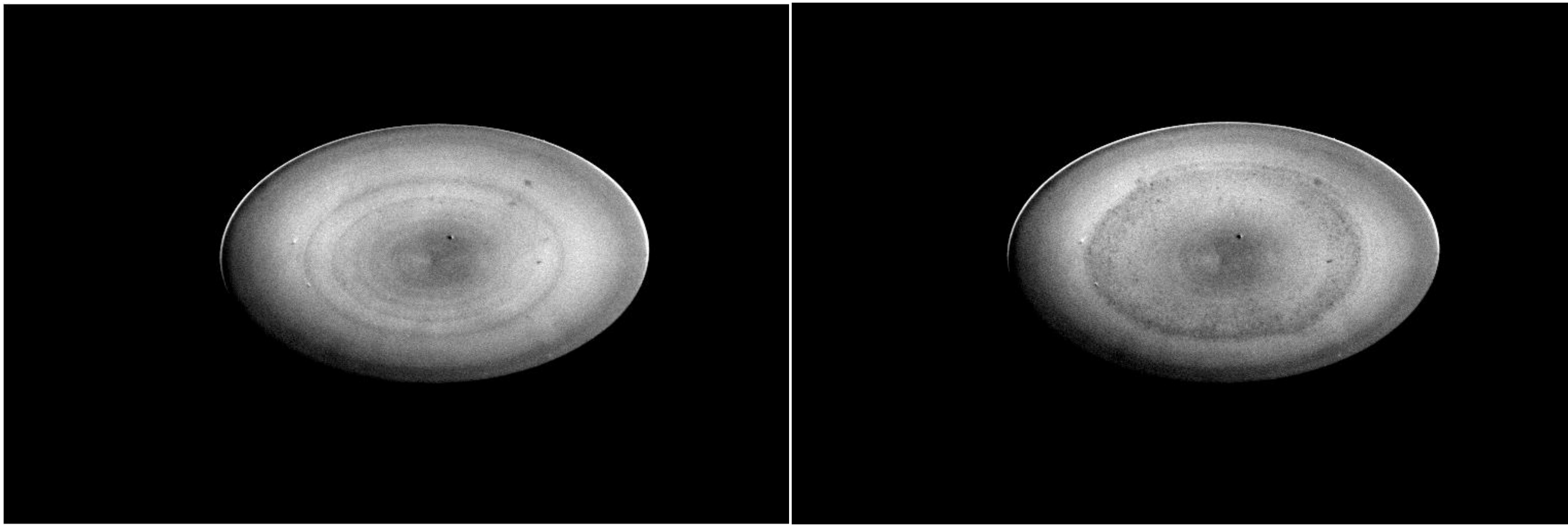

Significant cathode peeling was observed for the 2nd time
Prior observation was on an unheated cathode with full Marx pulse (Don't do this!)
Major concern was flakes of Os-Ru in the Marx column
Cause of flaking was not aggressively persued

# Two cathodes showing Os-Ru “peeling”



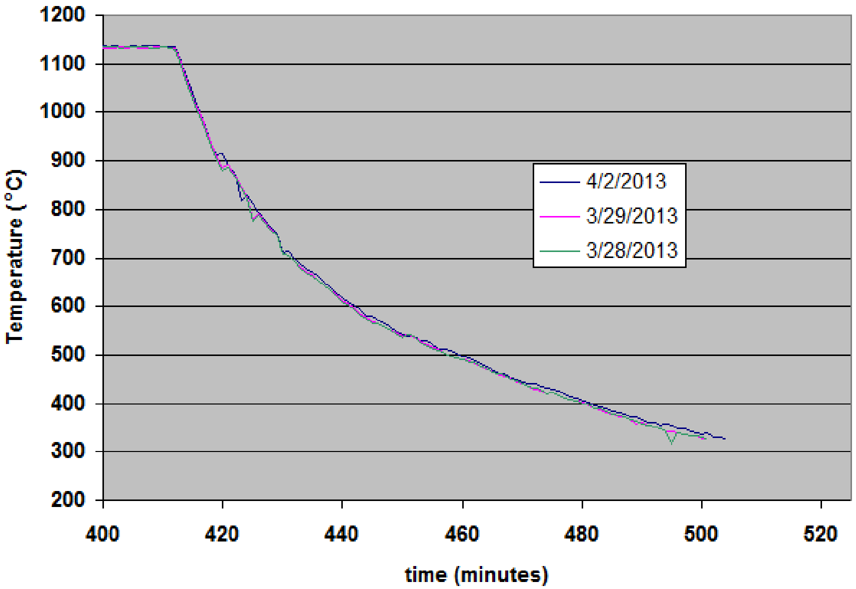


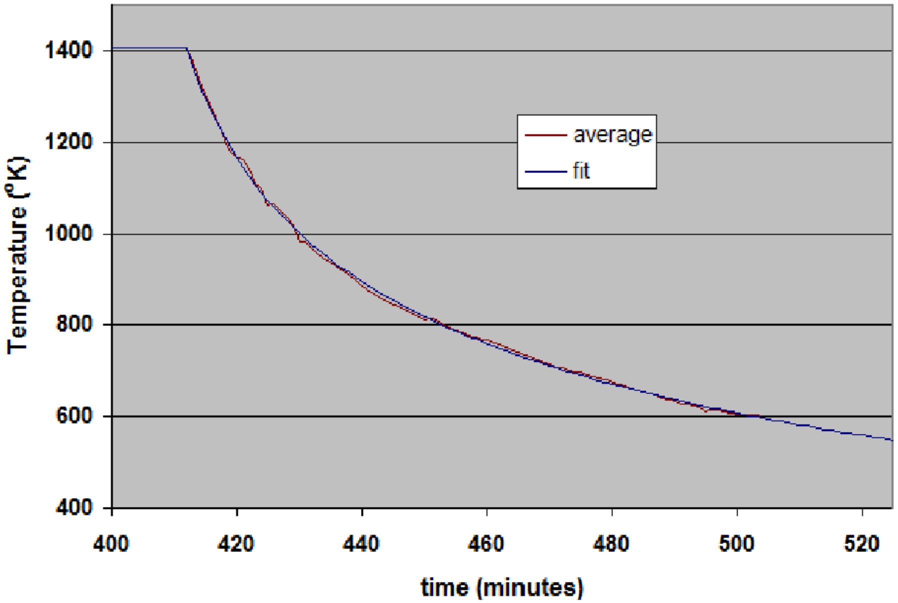
# Os-Ru "peeling" can be exacerbated by deliberate power loss



**Deliberate loss of power from standby power of 400 W (~600$^o$C) to ambient as heat dissipation is dominated by conduction introduces thermal stress on cathode surface. Os-Ru was not adequately bonded to tungsten substrate.**

# Cathode Cooling and Heat Transfer

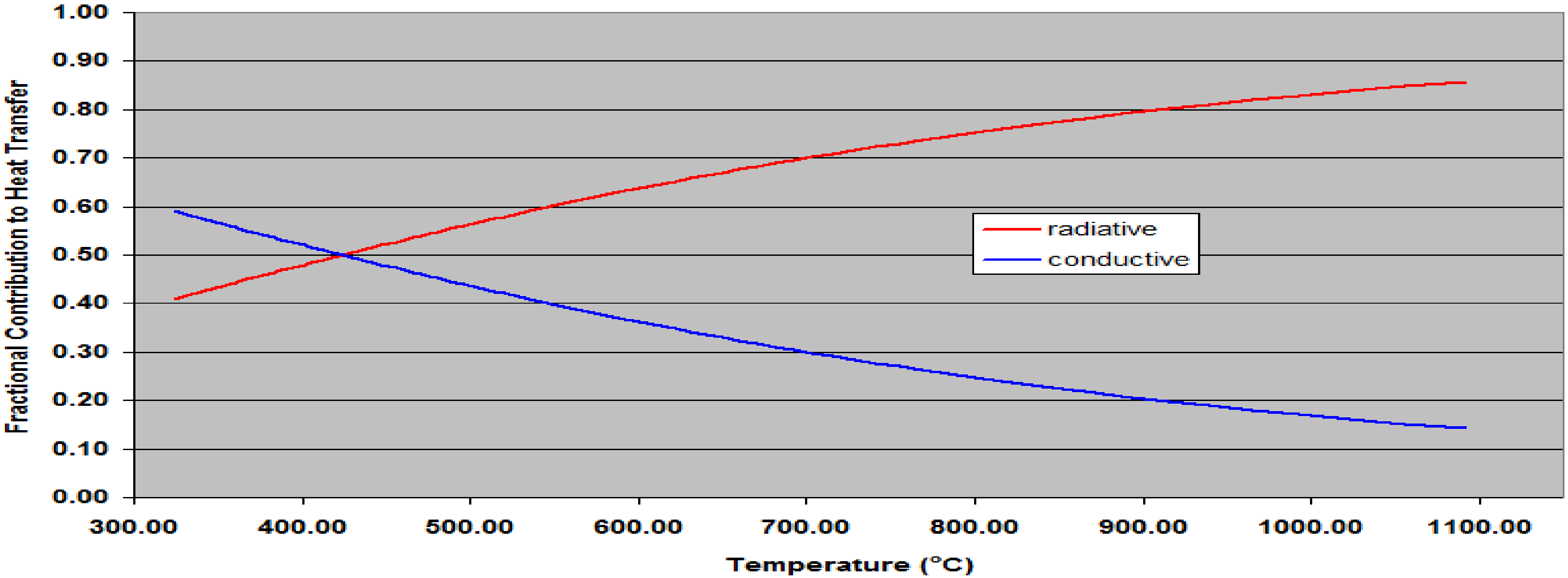



Temperature vs time for thermal cycle studies with an abrupt turn off of power at full temperature with an attempt to synchronize the turn off time

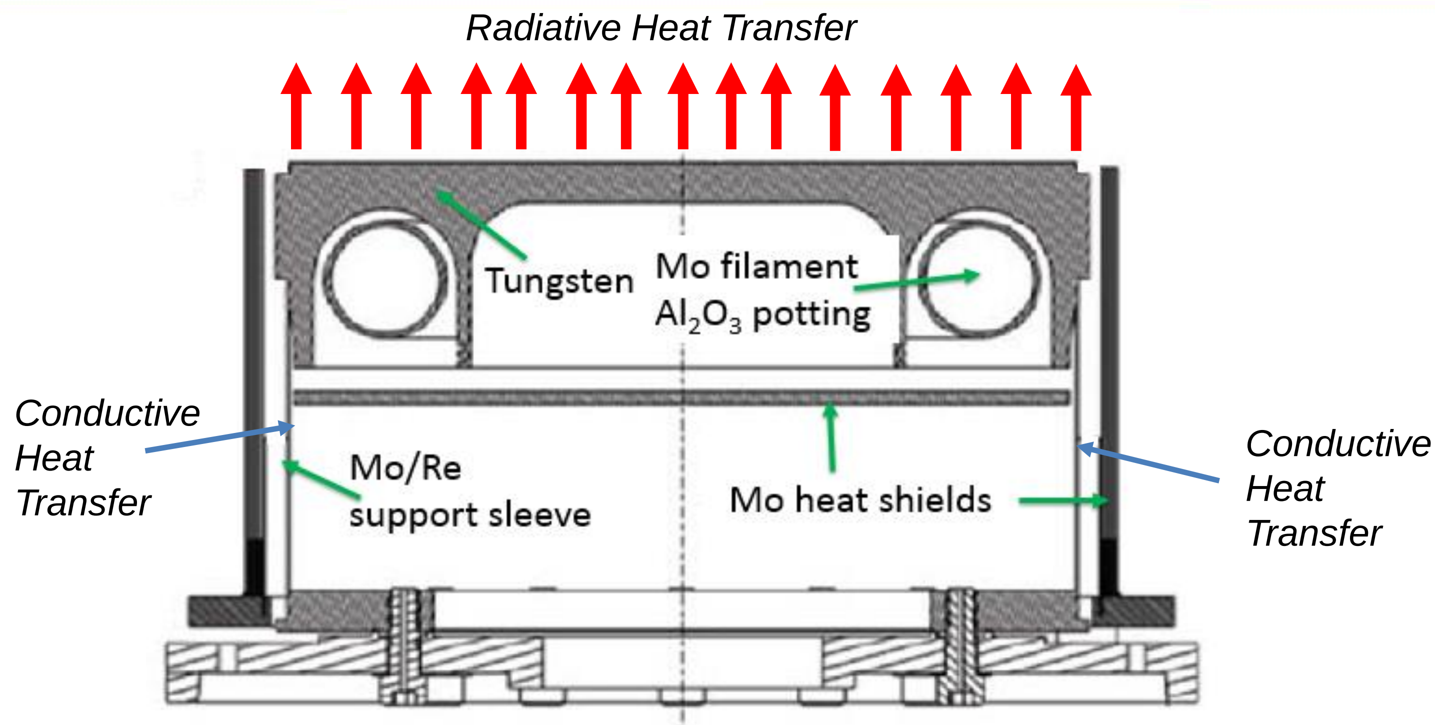
$$\frac{dT}{dt} = -a(T - T_o) - b(T^4 - T_o^4)$$

# Cathode Cooling and Heat Transfer




Fractional contribution of the radiative and conductive heat transfer as a function of the cathode temperature. Radiative heat transfer dominates above 500ºC. The choice of 400W (~630ºC) as the standby power means that cooldown from the operating temperature is dominated by radiative cooling which is essentially uniform across the cathode surface.

# DARHT-II Cathode X-Section




***Note: It takes only 400 W to heat the cathode to 630°C and 2100 W to add an additional 500°C due to the power radiating from the cathode.***

# Powering down the cathode

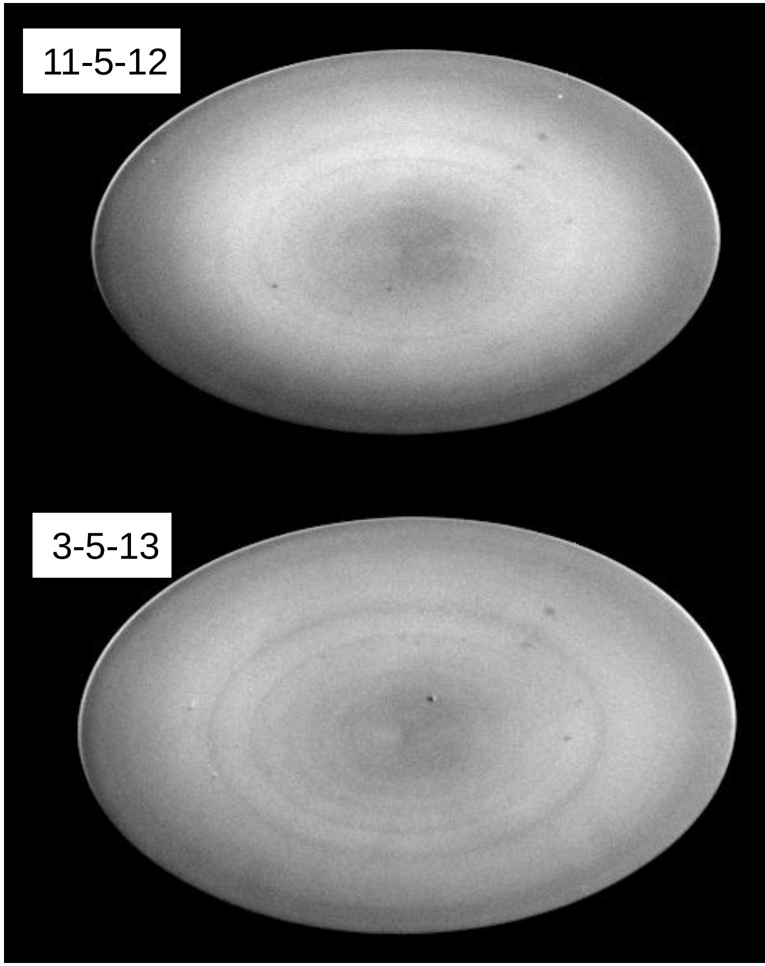
- Powering down the cathode from standby (400 W) to room temperature is critical to prevent peeling
  - Prior cathode did not degrade in loss-of-power event
- The objective is to very slowly reduce the cathode power so that the temperature is approximately uniform across the cathode surface.
- Procedure
  1. Reduce power in alternating steps of 20 and 30 W every 15 minutes.
  2. Pause for a minimum of 4 hours once the power reached 200 W.
  3. Resume step 1 until power is 20 W.
  4. Turn off cathode heater.

Note: Do not set the cathode to a power of 0 W. This is an indeterminate state due to the feed back loop that sets the AC current to maintain the cathode power at the desired set-point.

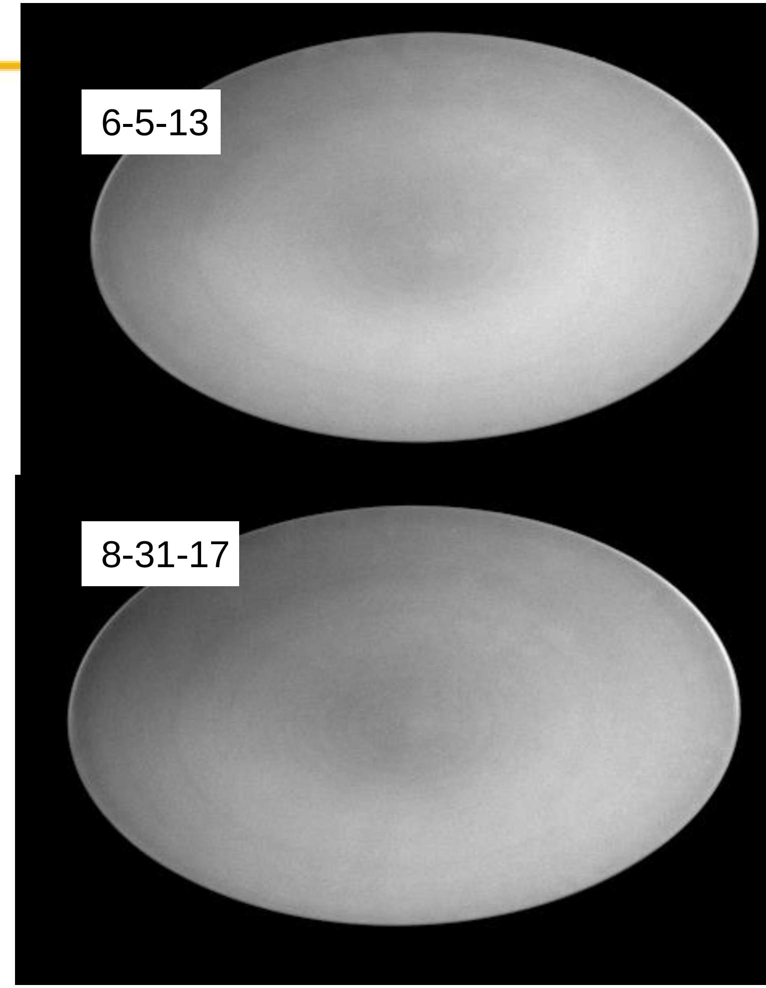
# Modifications to Fabrication and Activation Procedure

- **Fabrication Modification**
  - Prior to application of the Os-Ru surface coating the cathode is subjected to a chelation removing excess Barium near the surface
- **Last Activation Stage**
  - Previous
    - Hold the cathode at elevated temperatures (~1160$^{o}$C) for 2 hours
  - New
    - Hold the cathode at elevated temperatures (>1175$^{o}$C) for >4 hours
    - Slowly reduce cathode power over 4 hours to reach a temperature of 1130$^{o}$C
    - Hold the cathode at 1130$^{o}$C for 12 hours
- **No performance degradation for over four years**
  - Prior cathode lifetime (2509 hrs)
  - Present cathode lifetime (~500 hrs and counting)
- **Small reduction in current due to Barium depletion at the surface after two years corrected with small power increase**
  - Space charge limited emission recovered with modest increase in power from 2.6 to 2.7 kW

# Improvements to cathode activation and fabrication have led to more robust performance and longevity

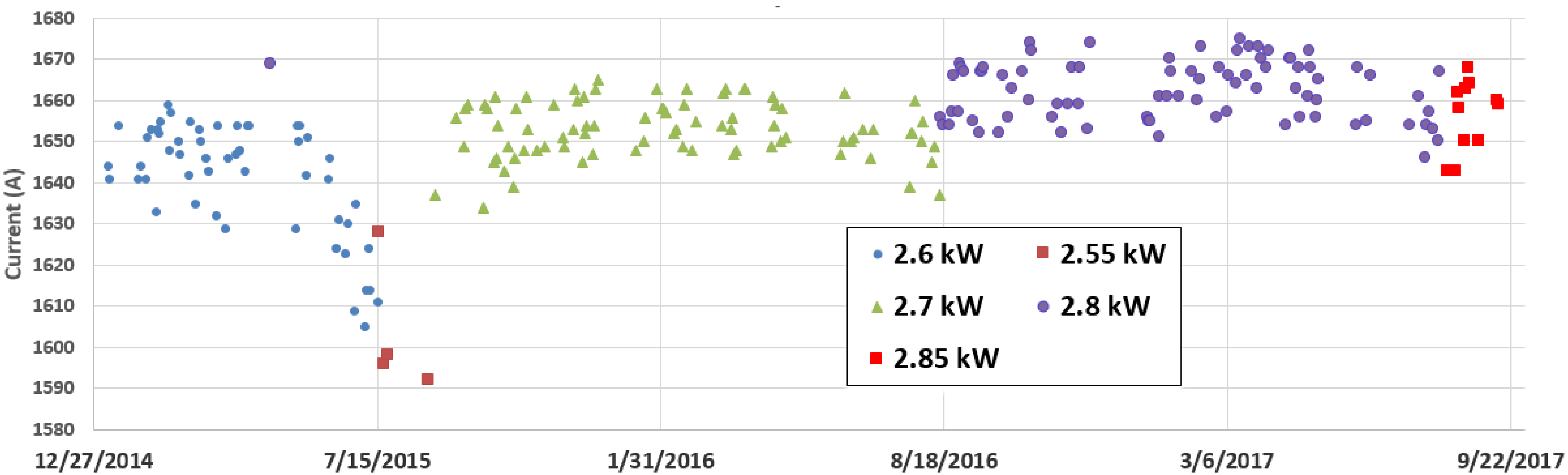



Prior cathode shortly after activation (top) and just prior to bucking coil replacement




Present cathode after activation (top) and last week

# Current on first shot of day




***July 2015: Observed slight reduction in beam current and an increase in temperature. Standard practice is to reduce power to maintain temperature of 1140ºC at this time. This resulted in a further reduction in current and temperature limited emission. After extensive studies, the problem was identified as Barium depletion on the cathode surface. This was compensated for by increasing the cathode temperature to drive more Barium to the surface. The slight increase in current at higher temperatures is due to a reduction of the A-K gap due to thermal expansion of the cathode and anode shrouds. We now operate the cathode at 1130ºC which should increase lifetime.***

# Cathode Lifetime

- The limiting factor in the cathode lifetime is the availability of Barium
  - Barium evaporates as the cathode is operated
    - The logarithm of the evaporation rate, E, is related to the operating temperature
      - $\phi$ is the activation energy in eV

$$logE = Const. - \frac{5040\varphi}{T}$$

- Higher Current density requires more activating material (e.g. Ba)
- Higher operating temperatures increase the Barium evaporation rate
  - Percent degradation/1000 hours (D)

$$D = 1.5\ x\ 10^{11} e^{-36200/T}$$

# Cathode Lifetime

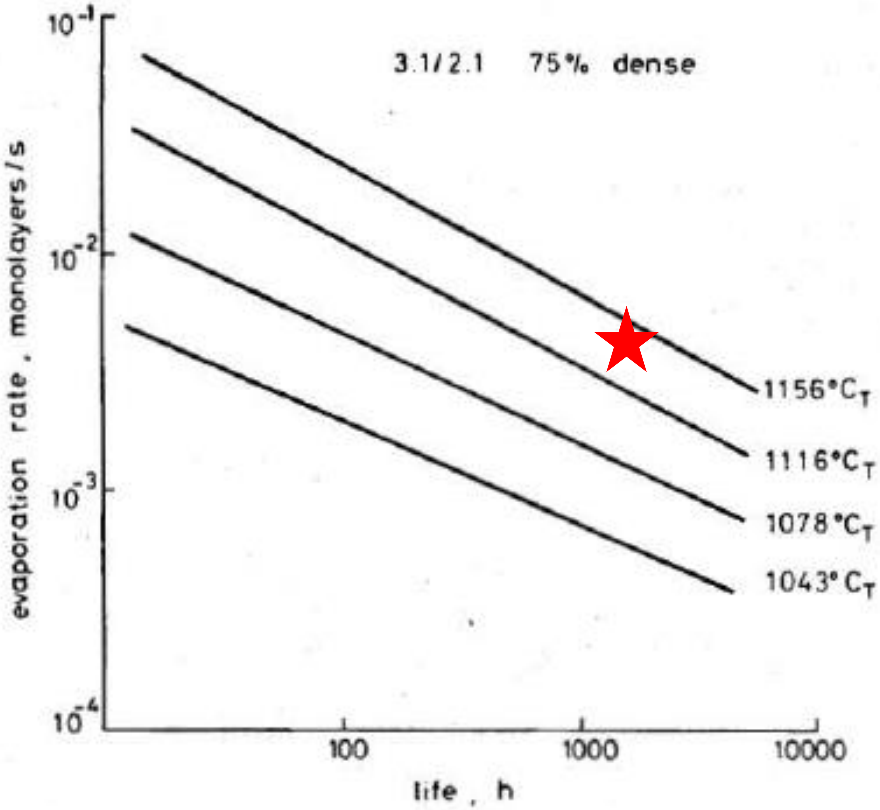



**Fig. 13** *Evaporation rate against life for a $3BaO:\frac{1}{2}CaO:1Al_2O_3$ cathode*

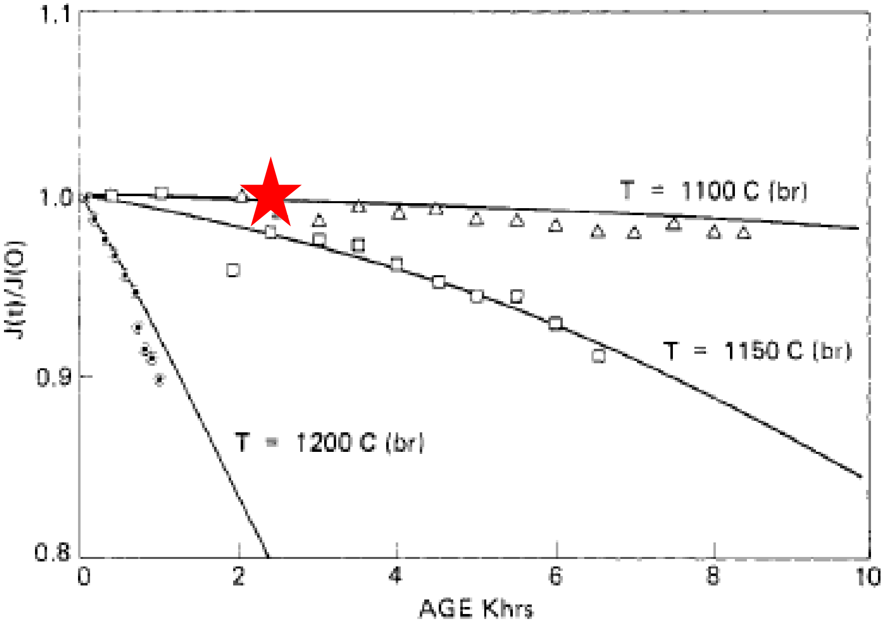



Figure 4 Accelerated M-type cathode run in a Pierce gun, initially set to be space charge limited.

# Cathode Lifetime – Barium Evaporation Rates

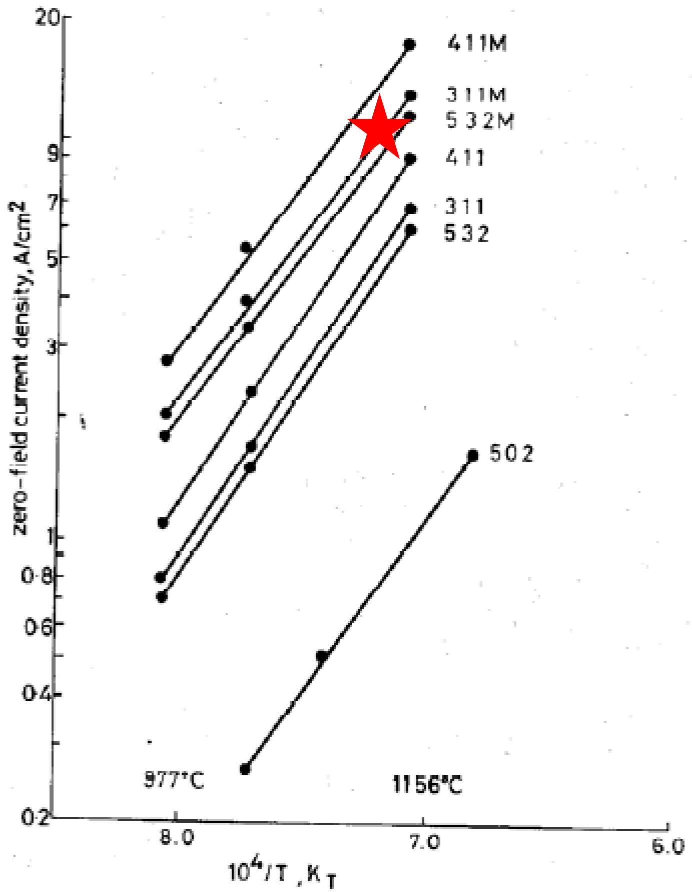



Fig. 16 *Emission of various cathode systems*

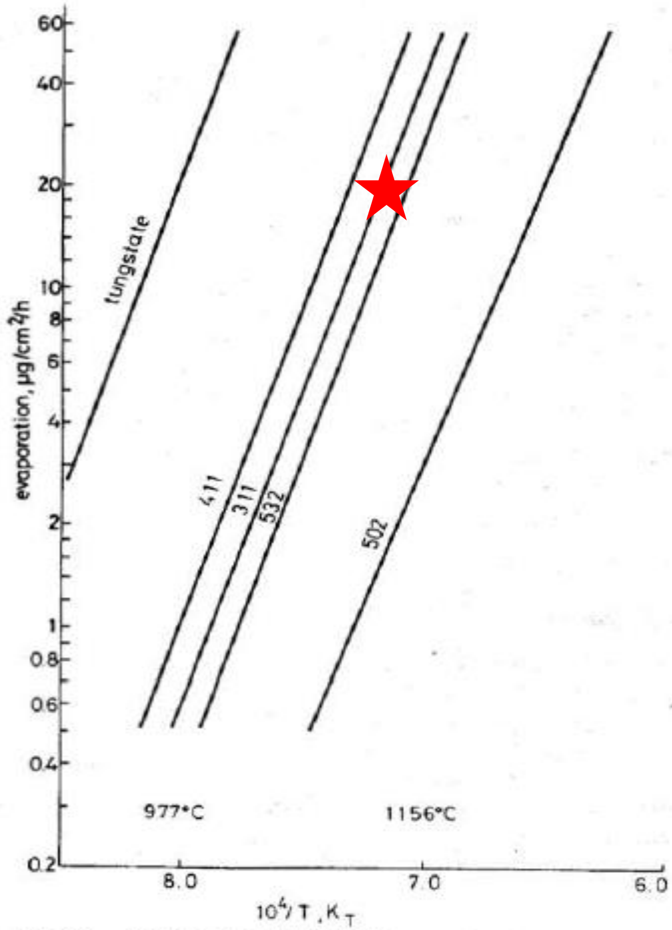
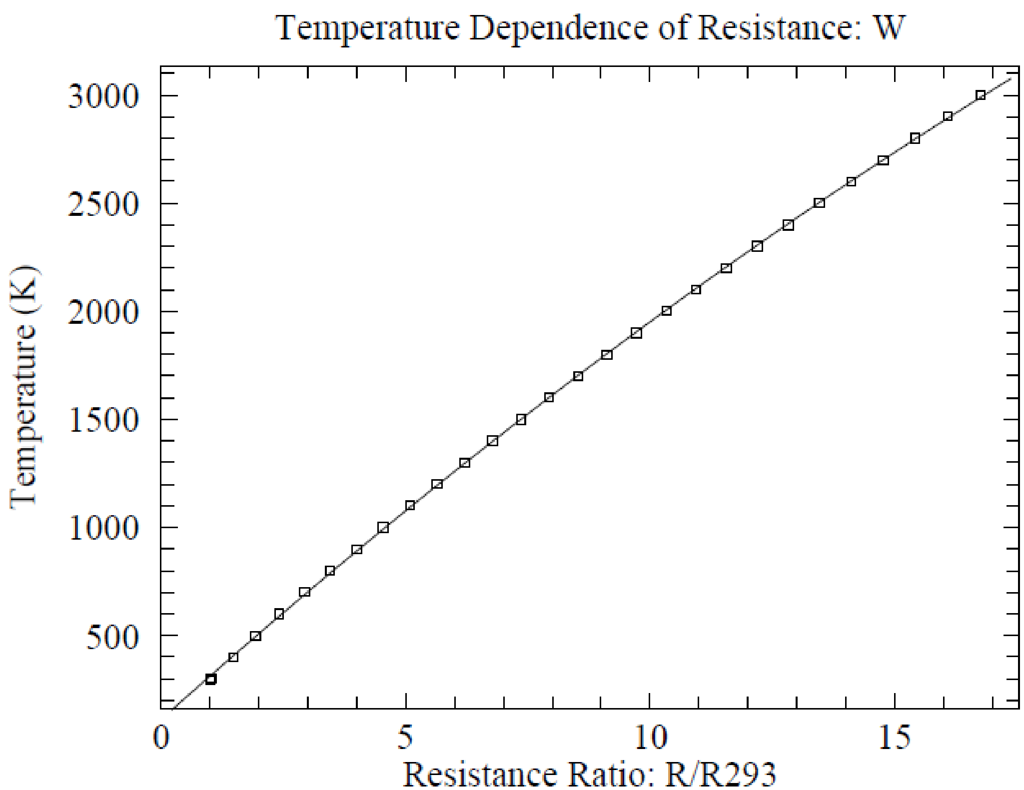



Fig. 14 *Barium evaporation rates*

# Cathode operation – Filament current and Power Supply

- The typical filament current at full power (2.6 kW) is about 60 A
  - 1130 -1135 °C
- The filament power supply can go to 3500 W
- The filament will burn out at ~75A
  - Limit to 72 A
- The filament current at standby (400 W) is 30.7 A
  - ~630 °C



# Pyrometers

- Three pyrometers are used to measure cathode temperature
  - Pyro 1 (Farr pyrometer)
    - Operating range 300 – 1200 $^{o}$C
  - Pyro 2 (Farr pyrometer)
    - Operating range 800 – 1200 $^{o}$C
    - Emissivity
    - This pyrometer is primary pyrometer
  - Pyro 3 (not a Farr pyrometer)
    - Operating range 300 – 1200 $^{o}$C
    - General purpose pyrometer

# Technical Notes on DARHT-II Cathode

- JASON Review
- Prichard Report
- Cathode Observations
- 2016 AECR Capability Review